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On scaling and mathematical modelling of large scale industrial flames

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ABSTRACT

Gaseous flames and pulverized coal flames are considered to examine relationships between lab-scale flames, semi-industrial scale and industrial-scale flames. The experimental data spans the thermal input range from the lowest scale of 30 kW to the largest of 12 MW with several intermediate scales. The primary questions are whether effects observed in lab-scale flames are scalable to industrial applications and whether mathematical models developed on the basis of lab-scale data are directly applicable to industrial flames.

It has been observed that disparity between the in-flame temperatures measured in lab-scale and in large-scale flames can be as large as 100–200 K due to different measurement techniques used. In lab-scale experiments one observes a strong interaction between turbulence and chemistry and the measured data is sensitive to small alterations to burner inputs and/or boundary conditions. The sensitivity almost disappears at large-scales since the convective mixings is the dominant (the slowest) mechanism. In other words, different effects are seen at small- and large-scales and different mechanisms are controlling. Although the paper is concerned with single flames, in our opinion, the conclusions are also relevant to gas turbines. Until genuine efforts are taken to develop a good understanding of combustion system scaling, the worlds of combustion science and combustion engineering will remain parted.

1. Introduction

The word “scaling” is frequently used in combustion science as for example in a sentence “NOx scales with temperature as …. “and here the verb “scales” may be replaced by “varies” without any loss of meaning. In this paper the word “scaling” is used in a different context. Here we consider situations where experiments are carried out in a university type laboratory and the question arises how to scale results of such experiments into industrial applications. For example, a burner generating turbulent flames of desired properties (stability, turndown, flame length, heat transfer rate, pollutants emissions) has been tested at a thermal input of 15–30 kW, or perhaps even at 300–500 kW, and it is to be scaled to a megawatt range, say 5–50 MW, expecting that the flame properties remain similar to those observed in the laboratory-scale experiments. An inverse situation is also relevant; an industrial burner, operating in a megawatt input range, is to be scaled down to say 10 kW size in order to carry out a flame characterization using a sophisticated laser-based diagnostics. Then, a question arises how to scale down the burner to such a small thermal input and preserve desired flame features. Indeed, it is desired to examine whether such scaling is at all possible?

Tremendous progress in computing speed and power (memory) as well as in computational methods, has brought CFD-based mathematical models to flame/burner engineering. RANS-based mathematical models are being routinely run on desktop computers of engineering companies whilst LES-models, which require an access to powerful computational facilities, become gradually available. Thus, one often comes across statements that the scaling problems described above do not exist any more since one may perform burner/flame design experiments in a university lab and use a sophisticated laser-based diagnostics to generate in-flame data for validation of a CFD-based

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mathematical model. After a tuning of the model to the in-flame data, the burner/flame scaling is then carried out using the mathematical model. It is demonstrated later that such a procedure is often bound to fail.

2. Relevant projects and publications

In the past, the scaling issue was given much more attention than currently. Pioneering works of Hottel [1] and Spalding [2] set up the scene. Twenty years after Spalding's paper [2], Weber [3] reviewed two scaling laws – the constant velocity and the constant residence time principles. There were only a few research projects to examine the scaling issue. In the 1977–1980 period, the International Flame Research Foundation (IFRF) and the Central Electricity Generating Board of the UK [4,5] carried out a series of experiments on heavy fuel-oil firing spanning the thermal input range from 0.5 MW to 33 MW and three sizes of furnace and four sizes (thermal inputs) of burner were used. In the 1990s, the IFRF in cooperation with the Gas Research Institute (with involvement of John Zink Company and the University of Michigan) carried out the Scaling-400 Study on natural gas burners spanning the 30 kW to 12 MW thermal input range (12 MW/30 kW = 400, so the project was named as Scaling-400) with intermediate inputs of 300 kW, 1.3 MW and 4 MW [3,6]. CFD-based mathematical modelling (RANS) was used to interpret the differences in NOx emissions of 4 MW and 12 MW high-NOx (unstaged) flames [7]. The Scaling-400 study was later extended to experiments on low-confinement 300 kW flames at Burner Engineering Laboratory (Sandia) [8,9]; the high confinement tests at 1.5 MW were performed at British Gas [10,11]. Inspired by the Scaling-400 study on swirling flames, British Gas, Gasunie (The Netherlands) and Gaz de France carried out a related study on 50 kW and 500 kW bluff-body stabilized natural-gas burners [12,13].

The IFRF has also carried out studies concerning scaling of pulverized coal flames spanning the thermal input range 2.5–12 MW [14–17]. The 12 MW burner has been scaled down to 2.5 MW thermal input using both the constant velocity and the constant residence time principles. High and low-NOx flames were produced and were probed to determine in-flame thermo-chemical structures. An analysis of the burner scaling (from 180 kW to 50 MW) in the context of NOx emissions using a CFD-based (RANS) mathematical modelling was presented in Ref. [18].

In conjunction with development of low NOx burners for pulverized coal combustion, Babcock-Hitachi Ltd already in the eighties of the last century, carried out studies [19] using two small-scale burners (Burners A and B of around 200 kW fuel input corresponding to 25 kg/h coal feeding rate) and Burner C of a 4 MW fuel input corresponding to 500 kg/h fuel feeding rate. One of the observations was that in order to match the low-NOx figures of the 4 MW burner in the 200 kW experiments, the 200 kW burners had to be modified so as to properly scale the physical size, the temperature and residence time of the fuel rich zone required for the NOx emissions reduction. Matching the char burnout was not possible [19].

The above cited papers were published before the year 2000 and since then the scaling issue disappeared from the research agenda. It is perhaps fair to say that, in this century, publications concerning combustion fundamentals focused almost exclusively on small-scale (university-type) flames. That is not to say that such flames are irrelevant for the scaling issue. To the contrary, research on simple (low thermal input, typically 20–40 kW) flames may be valuable for designers of combustion plants provided that a method for translating the small-scale findings to industrial applications is developed (scaling laws). Here for example the excellent work on turbulent combustion, organized through the Turbulent Non-premixed Flames (TNF) Workshop [20], provides a heap of data on piloted $CO/H_2/CH_4/N_2$ jet flames. Impressive laser based techniques (Raman and Rayleigh scattering, LIFs) have been developed [20,21] for temperature and (minor and major) species measurements. Plots of temperature versus mixture fraction and scalar dissipation rates are fundamental for characterization of the state of mixing and reaction progress. In addition to the Sandia burner producing piloted jet flames [20], bluff-body stabilized and swirl-stabilized flames were generated at Darmstadt [22], at Delft [23], Sydney [24] and Cambridge [25]. Consequently, there is a proliferation of papers reporting on both the measurements and the mathematical modelling (mainly Large Eddy Simulations) and reviewing them is beyond the scope of this paper. As a matter of fact, Bilger et al. [26] reviewed the progress in understanding turbulent combustion and underlined the key role of TNF; so did the more recent reviews of Peters [27], Pitsch [28] and Pope [29]. In the context of this paper, the question is how the data and their interpretations concerning these simple - low thermal input – jet flames can be used to design flames for industrial applications in a megawatt input range. In other words, does the small scale date reflect what goes on in industrial flames? Can then mathematical models, developed and validated against the small scale data, be used in predicting turbulent industrial flames?

3. Measurements in lab-scale and large-scale flames

3.1. Temperature

While examining flames spanning a large input range, say 20 kW to 12 MW, one should realize that different techniques are used for in-flame measurements. Although, in the 1990s, thermocouples were used for measurements in TNF flames [23], nowadays combined Raman/Rayleigh/LIF diagnostics has eliminated intrusiveness. In large scale flames, the in-flame temperatures are typically measured using either a bare thermocouple or, more frequently, a suction pyrometer (aspirating thermocouple). Although application of the combined Raman/Rayleigh/LIF diagnostics to furnace-confined flames is out of the question, one should at least establish typical differences when these intrusive and non-intrusive techniques are used. In Fig. 1(Top) both a suction-pyrometer (IFRF design) and a fine-wire thermocouple [30] (50 μm diameter, Pt/Rh 6–30% - type B) are used to measure gas temperatures at a traverse located 437 mm downstream of the 1.3 MW version of the Scaling-400 burner. The figure shows both the uncorrected thermocouple readings and the "true" gas temperatures obtained by correcting the readings for both radiation losses and thermocouple thermal inertia (furnace wall temperature of 1200 K). In the region where the gas temperatures exceed the furnace wall temperature, the "true" (corrected) thermocouple readings are typically 100–200 K larger than the suction pyrometry data. Fig. 1(Bottom) shows temperatures measured [10] 610 mm downstream of the 1.5 MW bluff-body stabilized (non-swirling) natural gas burner; the suction pyrometry data (the same pyrometer has been used as in Fig. 1(Top)) are compared with Coherent anti-Stokes Raman Spectroscopy (CARS) data (BOXCARS arrangement on nitrogen, measurement volume of around 20 mm length). Fig. 1 clearly demonstrates that temperatures measured using CARS are typically around 100 K larger than those obtained using the suction pyrometer. Although, in the past, single-pulse temperatures were made over the 135–296 K temperature range using CARS and a very good agreement was obtained with thermocouple readings [31], one should not expect such a good agreement at higher temperatures

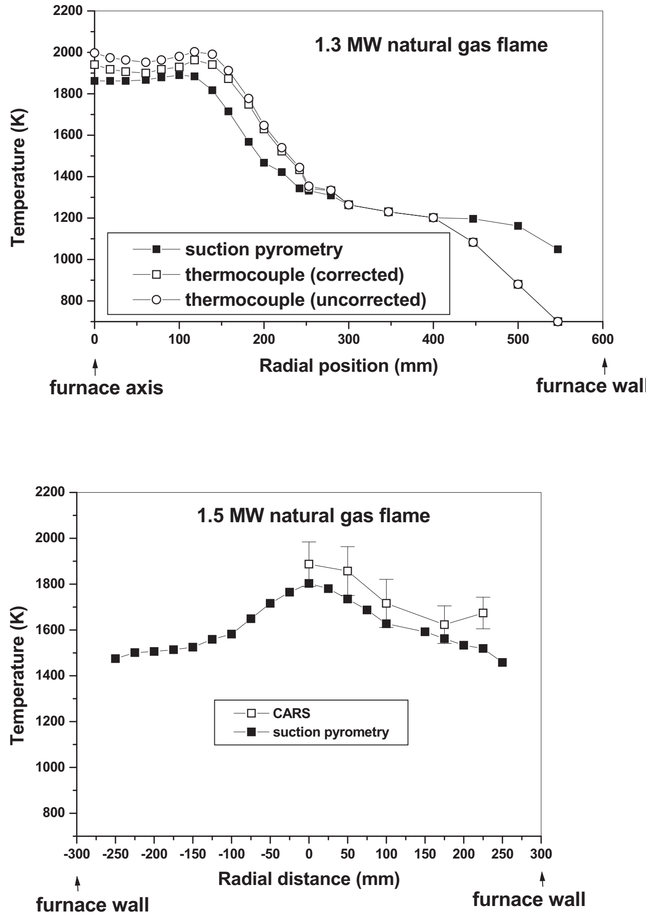

Fig. 1. Temperature measurements in natural gas flames. Top – measurements using suction pyrometry and fine-wire thermocouple at a traverse located 437 mm downstream of 1.3 MW version of the Scaling-400 burner [30]; Bottom – measurements using suction pyrometry and CARS at a traverse located 610 mm downstream of 1.5 ME bluff-body stabilized flame [10].

due to the ambiguity associated with the corrections for radiation. To our best knowledge, there are hardly any studies comparing performance of CARS and Raman/Rayleigh techniques with intrusive methods for measurements at elevated temperatures. One may expect that CARS and Raman/Rayleigh would provide somewhat similar temperatures (an analysis of the measurement errors associated with these techniques is beyond the scope of this paper), and they will remain around 100 K larger in the downstream part of flames and up to 200 K larger in the near burner zone if compared to temperatures determined using a suction pyrometer. As a matter of fact, by usage of a suction pyrometer the radiation error is overcome by (1) placing the thermocouple in a tubular passage through a ceramic radiation shield and by (2) aspirating the gas through a passage with an adequate sucking rate. The pyrometer thermocouple, being in equilibrium with the sucked gas, measures the sucked gas temperature. Thus, the non-intrusive laser-based techniques measure temperatures that are different to the ones determined by the pyrometry; the first ones are temperatures that fit the rotational spectrum of N_2 while the latter ones are the temperature of the gas sucked through the pyrometer. Temperature data shown in Fig. 1(Bottom) has been generated using CARS of around 20 mm measurement volume length while the pyrometer used was of a comparable (27 mmm) size (diameter).

In interpreting in-flame data we seek temperatures corresponding to local thermodynamic equilibrium (LTE) and we wish to have them at a high spatial resolution. While developing mathematical models, in the energy balance equation, the local thermodynamic equilibrium temperature appears. It is perhaps correct to say that when laser-based non-intrusive techniques are used, we obtain in-flame temperatures that are closer to the LTE temperatures than thermocouple measured or suction-pyrometer measured values. This important fact must be kept in mind while considering flames/burner scaling data.

3.2. *Major and minor species*

As described in Refs. [20,21], combined Raman and Rayleigh scattering allow for non-intrusive measurements of not only temperature but also concentrations of major species (O_2, N_2, CH_4, CO_2, CO, H_2O, H_2) in small-scale unconfined jet flames. LIFs are used to measure concentrations of OH, NO and CO [20,21]. In industrial-size flames, concentrations of major species (O_2, CO_2, CO) as well as NO and NO_2 are typically measured (on a dry basis - after removing water vapor from the sampled gas) using sampling probes and a set of analyzers. Sampling probes as small as a few millimeters in diameter and as large as a few centimeters are used depending on the physical size of the flame. Isokinetic sampling is mandatory and rapid aerodynamic quenching is needed. Generally, concentrations of O_2, CO_2, CO, NO and NO_2 can be measured with similar accuracies regardless whether non-intrusive or intrusive techniques are used provided that the sampling probe size is minimized. In other words, in measurements of major species, one does not expect such a strong disparity between the intrusive and non-intrusive techniques as in the case of temperature measurements as far as mean (not fluctuating) values are concerned.

4. Considerations on scaling of gaseous flames (single-phase combusting flows)

4.1. Fluid-flow similarity and confinement effects

Considerations on how to represent (scale) industrial-size flames in laboratory-scale experiments make sense only if the overall flow pattern is preserved while changing the scale. This, rather an obvious and simple-looking requirement, is often violated due to complex, and perhaps not fully understood, interactions between different burner streams as well as interactions between burner streams with recirculation zones formed in the furnace. In highly swirling flows, downstream disturbances (created for example by an undersized furnace exit) may propagate upstream altering the near burner flow pattern. We use here the Scaling-400 natural gas burner, see Fig. 2, to show an unexpected change (see below) to the flames issued from the burner during the burner scaling trials. As a matter of fact, Fig. 2 shows a family of geometrically-similar burners, with the scaling dimension D_o taking values of 27 mm, 87 mm, 180 mm, 317 mm, 549 mm for thermal inputs of 30 kW, 300 kW, 1.3 MW, 4 MW and 12 MW, respectively. The burners could be operated in standard (high-NOx) mode where all the fuel (natural gas) was injected through the central fuel injector located at the centerline (a steel pipe with a number of small holes through which the fuel is injected into the combustion air stream). By injecting the fuel via eight staged fuel pipes (spouts), the NOx emissions could be lowered reaching the lowest values at 80% or 100% staging (0% staging corresponds to the situation when all the fuel was injected via the central injector while 100% staging means that all the fuel was injected by the eight injectors equidistantly spaced on $2D_0$ circumference). The burners had identical fuel-to-air momentum ratio of 0.3 and the combustion air was swirled by a family of moveable block swirlers designed so that the pressure-drop across the swirler was the same for all the burner sizes (scales).

Scaling of the unstaged (high-NOx) flames has already been examined (see Fig. 7 of [3]) and the limitations of both the 30 kW and 300 kW experiments in representing the 12 MW trails have been underlined. Fig. 3 shows the NOx emissions dependence on fuel-staging at different thermal inputs indicating that the dependency was reproduced at all considered burner scales but the smallest (30 kW) burner size. Although attempts have been made [6] to explain this unexpected behavior observed in the 30 kW experiments, it is perhaps fair to say that reasons for the departure still remain unknown.

All the data presented in Fig. 3 have been obtained in experimental conditions where the furnace diameter to burner diameter (D_0 in Fig. 2) ratio has been maintained at 3.5. In other words, the confinement ratio $C = D_{furnace}/D_0$ has been kept constant. In order to examine the effect of the furnace size (confinement) on NOx emissions, additional experiments have been carried out. At 300 kW thermal input, the furnace has been made larger so that the confinement ratio has been increased to 7.5 [9]. As shown in Fig. 4, the enlargement of the furnace has resulted in rather small alterations to the burner behavior. However, when the 1.3 MW burner has been tested in a smaller furnace ($C = 2$), the burner performance has drastically changed, as shown in Fig. 4. As a matter of fact, the 1.3 MW burner trial carried out in the small diameter furnace has been conducted just to demonstrate the effects shown in Fig. 4. The differences in the 1.3 MW burner performance at confinement ratios of $C = 3.5$ and $C = 2$ are easily explainable by considering the role of the external recirculation zone formed in the furnaces. In large diameter furnace, a strong recirculation zone containing combustion products is formed and the staged fuel is injected directly into this zone resulting in NOx reduction. In the (too) small diameter furnace, this recirculation zone is small and ineffective so that the staged fuel mixes not with combustion products but directly with the combustion air stream producing high NOx emissions.

Fig. 4 demonstrates profound importance of the furnace/burner interactions. The effect is known to combustion engineers and the rule of thumb (IFRF origin) is that if the confinement ratio (C) is larger than around three, the furnace wall direct impact on the near burner zone can be neglected. That is not to say that the experimental results generated using free (unconfined) non-swirling flames are then directly applicable to low-confinement combustion. Not at all; if for example the free turbulent jet-flames of the TNF-Workshop were to be placed in furnaces and pilots (ignition sources) of the flames were to be removed, the resulting combustion patterns would be substantially different to those observed and reported at the TNF-Workshops and relevant publications. The interaction between large-scale and small-scale turbulence would be substantially altered by the in-furnace recirculation. With no pilots, the flames would ignite far downstream or perhaps no ignition would be feasible. It is perhaps fair to say that the TNF-flames provide the basis for the recent developments in turbulent combustion [26–29] and it is assumed that mathematical models describing turbulence-chemistry interactions, developed on the basis of these low-Reynolds number piloted flames, are applicable to industrial-scale combustion. It is doubtful whether the mathematical models

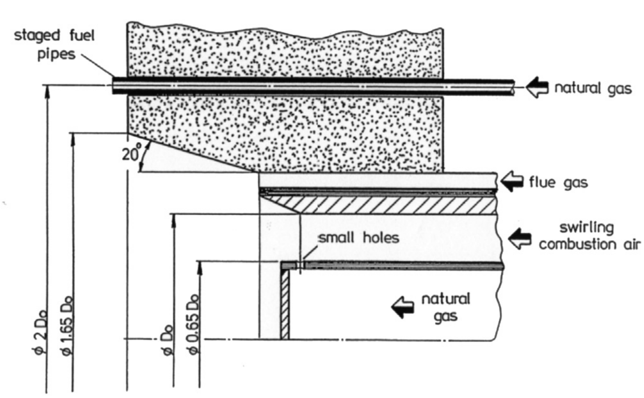

Fig. 2. Scaling-400 Natural Gas Burner. D_o represents a burner diameter which varies with scale (thermal input).

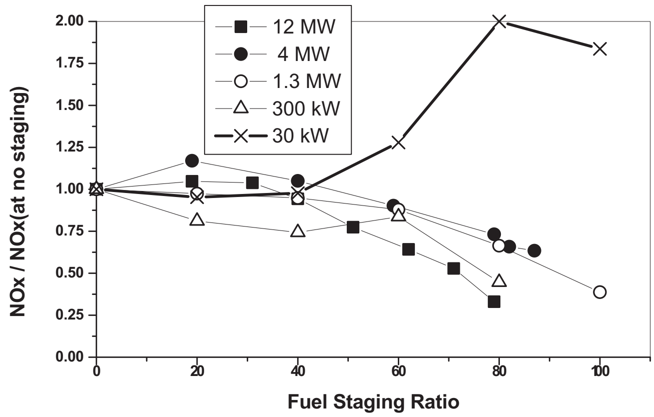

Fig. 3. The Scaling 400 Data [32–36] concerning performance of the burner shown in Fig. 2 at fuel staging (low NOx) conditions.

tuned and validated against the in-flame data generated in these confinement-free flames would be able to perform well in simulating confined-combustion.

4.2. Reynolds number dependence

Usually research on fluid mechanics of combusting flows, which is being carried out in university-type labs, is limited to flows whose Reynolds numbers seldom exceed 100,000. Reynolds number of the TNF flames (see Table 1 in Ref. [20]) are in the 8,300–44,800 range while the Reynolds number of the combustion air stream for the smallest (30 kW) burner of the Scaling-400 study is 16,300 while for the largest (12 MW) 331,400. In full-industrial scale applications, Reynolds numbers approach typically half of a million. It has been demonstrated previously [3], and partially in this paper, that relating the 30 kW and the 300 kW results to large scales flames is difficult. To what extend the Reynolds number effect plays a role here is not easy to determine. However, it is clear that the convective time scale, which magnitude can be estimated as D_0/U_0 (U_0 is the characteristic burner velocity, D_0 is the burner diameter), is typically in lab-scale flames (including TNF flames) much shorter than in industrial-scale ones. In other words, in lab-scale flames we observe and measure strong effects of combustion chemistry while in large-scale flames the convective time, related to macro-mixing, is the limiting factor. Can then mathematical models, developed on the basis of lab-scale experiments, perform well in predicting industrial scale-combustion? There are publications, see for example the work of Al-Fawaz et al. [37], showing that NOx emissions of 67 kW and 266 kW burners, scaled using constant-velocity principle, could be predicted using the same CFD-based model. However, it remains unknown whether predictions in megawatt range would be accurate. One should bear in mind that the relationship between chemistry and turbulent mixing is strongly scale-dependent.

5. Considerations on scaling of pulverized-coal flames (two-phase combusting flows)

Consider again experiments, carried out at a small scale and aiming at a development of a burner which is to be scaled to tens of megawatt thermal input. This time, we focus on two-phase flows, namely on pulverized coal combustion (similar considerations could also be given to spray combustion). As a matter of fact, numerous research projects were carried out over the last two decades aiming at providing a guideline for designing low-NOx burners for combustion of coals with oxygen. One of the most impressive projects has

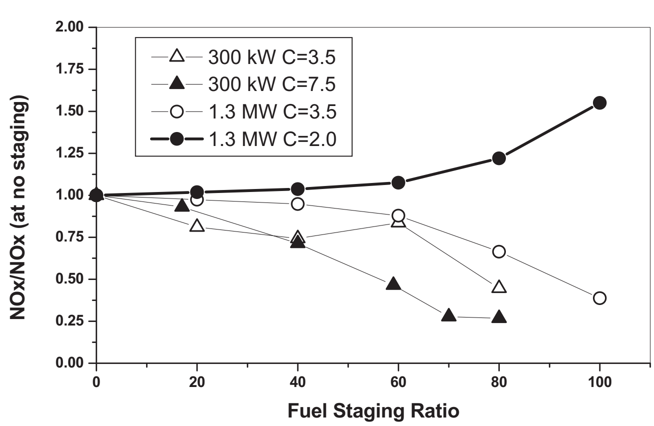

Fig. 4. The effect of confinement on performance of the burner shown in Fig. 2. The burner performance data has been generated in various projects – for 300 kW input in Refs. [9,36] while for 1.3 MW in Refs. [11,35]. C is the furnace to burner diameter ratio.

been undertaken at the RWTH Aachen (Germany) with a series of tests carried out using a 40 kW oxy-fuel burner facilitating pulverized coal combustion in CO_2-O_2 mixtures. The activities included the development of the burner concept [38,39], detailed diagnostics of the flames [40,41], investigations of flame stability mechanisms [42]. Moreover, a CFD-based (RANS) mathematical model was developed to assist in the burner design venture [38,39]. The 40 kW burner version, designed and optimized to provide stable flames with oxygen content (in CO_2 and H_20 mixtures) in the 21–27% range was scaled to 80 kW input using the constant residence time principle and tested in the same furnace. The authors concluded that scaling of the burner to full-industrial scale (70 MW) was impossible [38,43] and this is also our opinion. At a 40–80 kW thermal input, bench-scale burners are extremely compact due to the lack of space and when for example air-staging is needed either to provide flame stability or to reduce NOx, neither near-burner fluid mechanics nor staging effects are scalable with the current state of combustion science. The key issue - which is not scalable - is the interaction between the solid-phase (coal particles trajectories) and the swirling air stream; the interaction determines both flame stability and NOx characteristics. The point is illustrated in Fig. 5 showing the Aerodynamically Air Staged Burner scaled over the 50 MW to 178 kW range using the constant velocity principle. Thus, for all the burner versions shown in Fig. 5, the combustion air velocity is 40 m/s while the coal transporting air jet is issued with 20 m/s velocity. Fig. 5 shows CFD-computed (RANS) trajectories of coal particles (left hand side) and flame regions where volatiles are given off (right hand side). In the 50 MW version of the burner, the coal particles give off volatiles mainly in the air stream. In the 0.9 MW and 0.176 MW flames, a substantial fraction of volatiles is given off inside the swirl induced internal recirculation zone which is depleted in oxygen. Scaling the burner to 40–80 kW inputs results in flame blow off. Not surprisingly, in the Aachen's flames the injection velocities are for the primary (coal-transporting) jet, and for the swirled-air stream around 10 m/s and 16 m/s, respectively with only 45% of the total combustion air supplied through the burner; the remaining 55% - named as staged air – is injected along the furnace wall (see Fig. 4 in Ref. [40]). That is required to generate stable flames at 1.2 inlet swirl number at 40–80 kW fuel inputs.

Examining Fig. 5 one may argue that the constant velocity scaling principle is inadequate. Indeed, the constant residence time principle has also been scrutinized in conjunction with type-2 (high-NOx) flames shown in Fig. 5 and more complicated type-1 (low-NOx) flames [14–18]. The conclusion has been that the constant residence time principle is indeed superior to the constant velocity principal and it can be applied when scaling burners larger than 2–3 MW inputs. Unfortunately, it also breaks down in the low-thermal input range.

In the authors' opinion, we do not have enough knowledge to relate observations made in two-phase swirling combusting flows of low thermal-inputs to industrial applications. These seem to be two different worlds. It has been suggested that scaling-laws for pulverized coal combustion should include Stokes number scaling. Indeed, milling the coal finer (micronized coal) for experiments at 30–80 kW inputs has been suggested but, to our best knowledge, never thoroughly tested. This is however one aspect only. Another one is concerned with the swirl number since a typical assumption is that the (inlet) swirl number is to be kept constant while scaling. Due to the appearance of the burner radius in the denominator of the swirl number (see for example [44–46]), at small radii the number becomes disproportionally large. The issue, whether the swirl number (which one? There are several [46]) is an appropriate scaling criterion to relate small swirling jets to large ones, is still unresolved.

More recently a number of projects have been carried out where simply non-swirling jet flames of 10–30 kW thermal input were issued into vertical furnaces to compare flames of refuse derived fuels [47] and various biomasses with flames of known coals [48,49]. The jet flames are of low Reynolds numbers (5, 800 for the fuel jet and 2,600 for the combustion air stream; both calculated at the burner inlet for 15 kW input) and no pilots are used for ignition. The ignition is provided by both the external recirculation zone ($C = 4.2$) and radiation from the furnace walls which are electrically heated to desired temperatures. Although such experiments provide information about the effect of particle size, moisture content, volatile matter content, or generally fuel properties, on flame ignition, their direct applicability to industrial-scale combustion is also not straight forward.

In the context of the above discussion we come back to the question whether CFD-based mathematical models of pulverized coal combustion, which have been developed and tested using lab-scale data, are applicable to industrial flames. Before we elaborate on the question, we observe that the LES model of a 100 kW flame [50] had to be massively modified [51] in order to simulate the 2.4 MW semi-industrial scale flame. Perhaps, it is also fair to say that the quality of the LES predictions [50,51] do not match the quality of the RANS predictions. The quality of the RANS predictions has been very good not only for the 2.4 MW flame [52,53] but also for both type-2 (high-NOx) and type-1 (low-NOx) flames of many other thermal inputs, tested up to 12 MW [18]. An answer can be given by stating that LES of pulverized coal combustion is in its infancy but this in an easy way out. In our opinion, the primary reason for the success of the RANS models [18,52,53] is that they have been developed on the basis of measurements in flames larger than 2 MW. Reynolds numbers of the combustion air (swirling) streams have been 50,000 for the 2.4 MW burner while 110,000 for the 12 MW and the inlet swirl number has been kept constant at 0.9 (see Fig. 5). In such flames advection (macro-mixing) of reactants expressed again as convection time scale D_0/U_0 is in the 6 ms (2.4 MW) to 12 ms (12 MW) range and is much larger than any time-scales concerning chemistry of volatile matter gas-phase reactions with oxygen. Furthermore, for such large burner radii, the swirl number is likely to be a good criterion. Thus, tuning the eddy-dissipation model at 2.4 MW scale (by adjusting the model constant to 0.6 [53]) provided good equality predictions at thermal inputs larger than 2.4 MW. The same RANS model was also used to compute flames of 0.9 MW and 0.178 MW thermal inputs (see Fig. 5), unfortunately the quality of the predictions could not be assessed due to the lack of the measured data. Finally, the RANS model predicted no stable combustion at thermal inputs lower than 0.176 MW.

The corollary of the above analysis is that different effects are being observed in lab-scale experiments, in semi-industrial trials and in industrial applications. At a lab-scale, due to the convective-mixing time-scales being comparable with the chemistry scales, we observe strong interactions between turbulent mixing and chemistry. In other words, small alterations to the burner inputs result in substantial changes to the flames. This sensitivity almost disappears at large scales since the convective mixings is the dominant (the slowest) mechanism. Thus, it is unlikely that mathematical models, LES or RANS, developed and tuned at a lab-scale will perform properly in industrial applications without substantial modifications and/or re-tuning. By examining the recent papers of Yamamoto et al. [54,55], one may get an impression that LES models developed and validated against lab-scale data [54], provide automatically excellent predictions of industrial boilers [55]. In the light of this paper, this is not possible. We presume in the Babcock-Hitachi's work [54,55], a tuning and a testing of the LES model against semi-industrial scale data took place but it has not been reported.

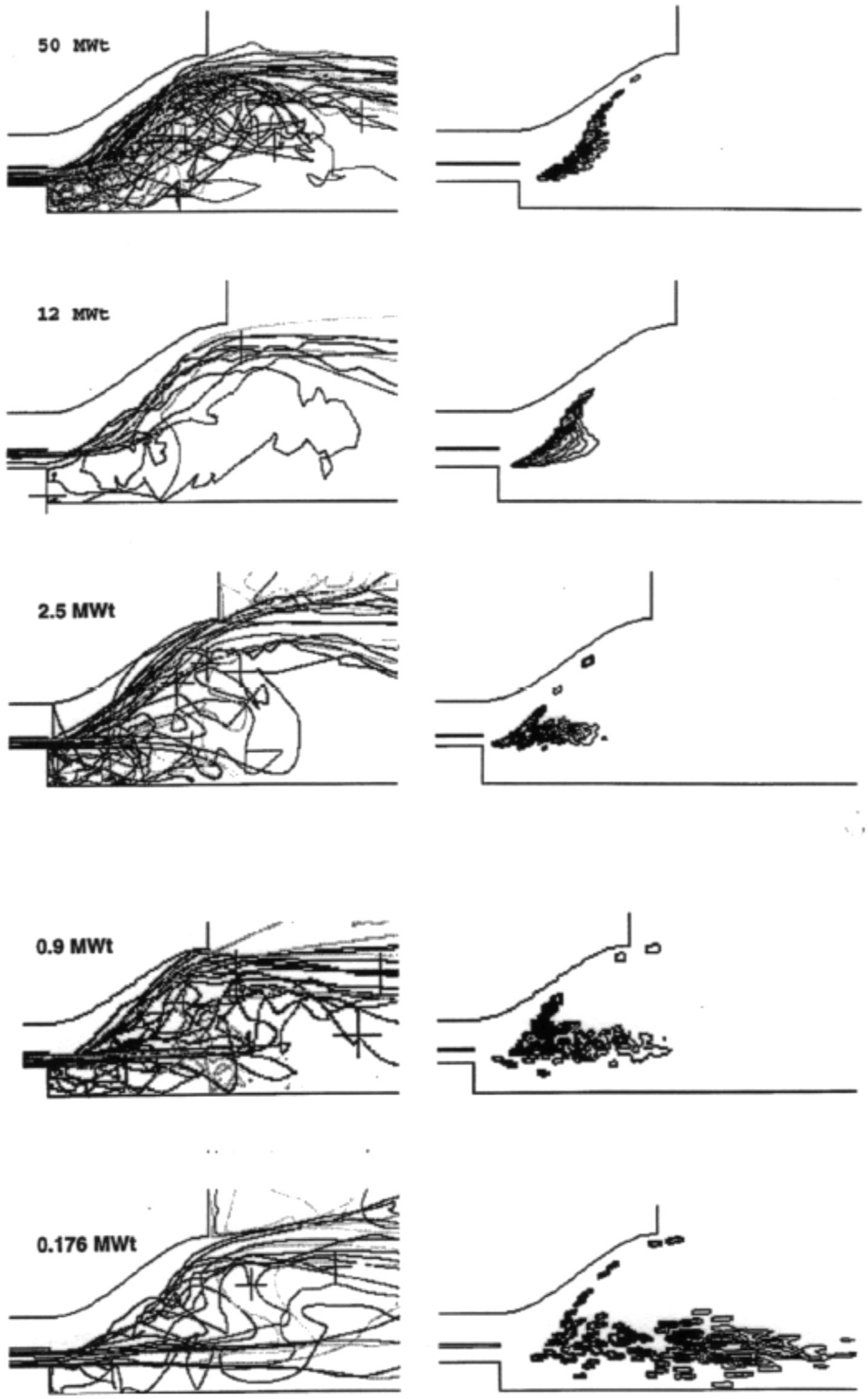

Fig. 5. RANS simulations. Particle trajectories (left hand side) and regions where volatiles are given off (right hand side) in an Aerodynamically Air Staged Burner scaled using constant velocity principle over a thermal input range of 50 MW–0.176 MW. The swirl number of the combustion air stream is kept constant at 0.9.

We wish to finish the discussion with a general remark. Although the paper is concerned with single flames, in our opinion, the conclusions presented below are also relevant to gas turbines.

6. Conclusions

On the basis of the above analysis concerning lab-scale, semi-industrial scale and industrial-scale flames, the following has been concluded:

(a) In-flame temperatures measured using non-intrusive laser-based techniques are typically 100–200 K larger than those measured using thermocouples or suction pyrometry. This is seldom accounted for during development and validation of CFD-based mathematical models.
(b) In lab-scale experiments one observes a strong interaction between turbulence and chemistry and the measured data is sensitive to small alterations to burner inputs and/or boundary conditions. The sensitivity almost disappears at large-scales since the convective mixings is the dominant (the slowest) mechanism. This is the primary reason for difficulties in relating lab-scale data to industrial-applications. In other words, different effects are seen at small- and large-scales and different mechanisms are controlling.
(c) The effect of confinement (furnace) on flames cannot be ignored; confinement may exert a profound effect on ignition, flame length, pollutants emissions. Experiments on free (unconfined) flames are hardly scalable to confined situations.
(d) It is unlikely that CFD-based mathematical models, LES or RANS, developed using lab-scale data can be directly applied to industrial-flames without substantial modifications and verifications against large-scale data
(e) Recent publications on combustion fundamentals focus almost exclusively on lab-scale experiments and on mathematical description of such experiments. Consequently, combustion engineers find limited relevance of such activities to engineering. Until genuine efforts are taken to develop a good understanding of combustion system scaling, the worlds of combustion science and combustion engineering will remain parted.

Dedication

The reader will notice that the paper is based on the work of the International Flame Research Foundation (Ijmuiden, The Netherlands) which spans almost two decades of research of the last century. The flame scaling issue was one of the key topics of the IFRF and, as pointed out in the text, it still remains unresolved. Dr. Roy Payne, Scientific Manager of the IFRF in the period January 1977–December 1979, was instrumental in organizing and executing the scaling project with CEGB [4,5]. Roy passed away on the 1st September 2015. A year before, I (RW) visited Roy at his place at Santa Barbara, CA; obviously we talked at length about scaling of combustion systems.

On December the 8th, Professor János (John) Beér passed away in Winchester (USA). John was the Head of the IFRF Research Station in the 1960–1963 period and later, being already a MIT professor, acted as the Superintendent of Research of the Foundation. At that time, the Research Station at Ijmuiden was directed by Peter Roberts and I acted as the Scientific Manager. During that period, I had numerous discussions with John in particularly on swirling flows and flames [44–46] – another key research topic at Ijmuiden. It is perhaps fair to say that John's research philosophy made a profound impact on the Ijmuiden's research team.

We dedicate this paper to the memory of Dr. Roy Payne and Prof. János Beér - the two remarkable colleagues and friends.

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